NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-403

Base Pressure Distribution of Two Blunted Cones at Mach Numbers From 0.3 to 0.8 and 1.81 to 3.51

Donald W. Kurtz

W. Russell Kerr

JET PROPULSION LABORATORY
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Approved by:

Bain Dayman, Jr.

Bain Dayman, Jr., Manager
Aerodynamic Facilities Section

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Abstract

To determine the detailed base pressure distribution on two blunted cones, a wind tunnel test was conducted in the JPL Supersonic Wind Tunnel. The two models, a 60-deg half-angle cone and a 45-deg half-angle cone, were investigated through a Mach number range of 0.3 to 0.8 and 1.81 to 3.51 at angles of attack of 0 to 20 deg. The subsonic wake shape and base pressure were highly insensitive to body shape and angle of attack changes in the range investigated. At supersonic Mach numbers, the base pressure was a distinct function of the wake-neck diameter, which decreased with increasing Mach number. The Reynolds number had a distinct influence on the viscous mixing and wake boundary layer. In the transition region from laminar to turbulent wake, an increase in the Reynolds number resulted in a reduction in the base pressure ratio.

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I. Introduction

Recent interest in wake phenomena has focused attention on the separated flow region behind bodies, particularly for axially symmetric transonic and supersonic flow. The base flow picture and, in particular, the base pressure are of significant importance for bodies that approximate reentry shapes. In certain cases, the base pressure drag can amount to as much as two-thirds of the total drag of a body of revolution (Ref. 1). Many applications to reentry problems require a knowledge of base pressure variations. Aft cover ejection or drogue deployment during reentry are two examples. This investigation involves a detailed base pressure distribution on two blunted conical reentry shapes in a range of Mach numbers from 0.3 to 0.8 and 1.81 to 3.51. The major results of the investigation are presented herein.*

*The complete experimental results of the program are contained in SR 900-175. This publication is available upon request to J. Jackson, Support Section, Technical Information and Documentation Division, Jet Propulsion Laboratory.

II. Test Description

A. Tunnel

The JPL 20-in. Supersonic Wind Tunnel (Ref. 2) is a continuous flow, variable density facility utilizing a two-dimensional flexible nozzle, which can provide an infinite choice of test-section Mach numbers up to $M = 5$. Subsonic Mach numbers may be reached by setting the nozzle area expansion ratio at one and adjusting the second throats to provide the proper pressure ratio. Recent calibration and yet unpublished data indicate good uniform flow throughout the test section at these Mach numbers.

B. Model

The models consisted of a 45-deg half-angle cone and a 60-deg half-angle cone with sharp edge radii (Fig. 1). Both models had a nose radius to base diameter ratio of 0.1. The 2-in. diameter aluminum cones were both mounted on a common base that was mounted on a

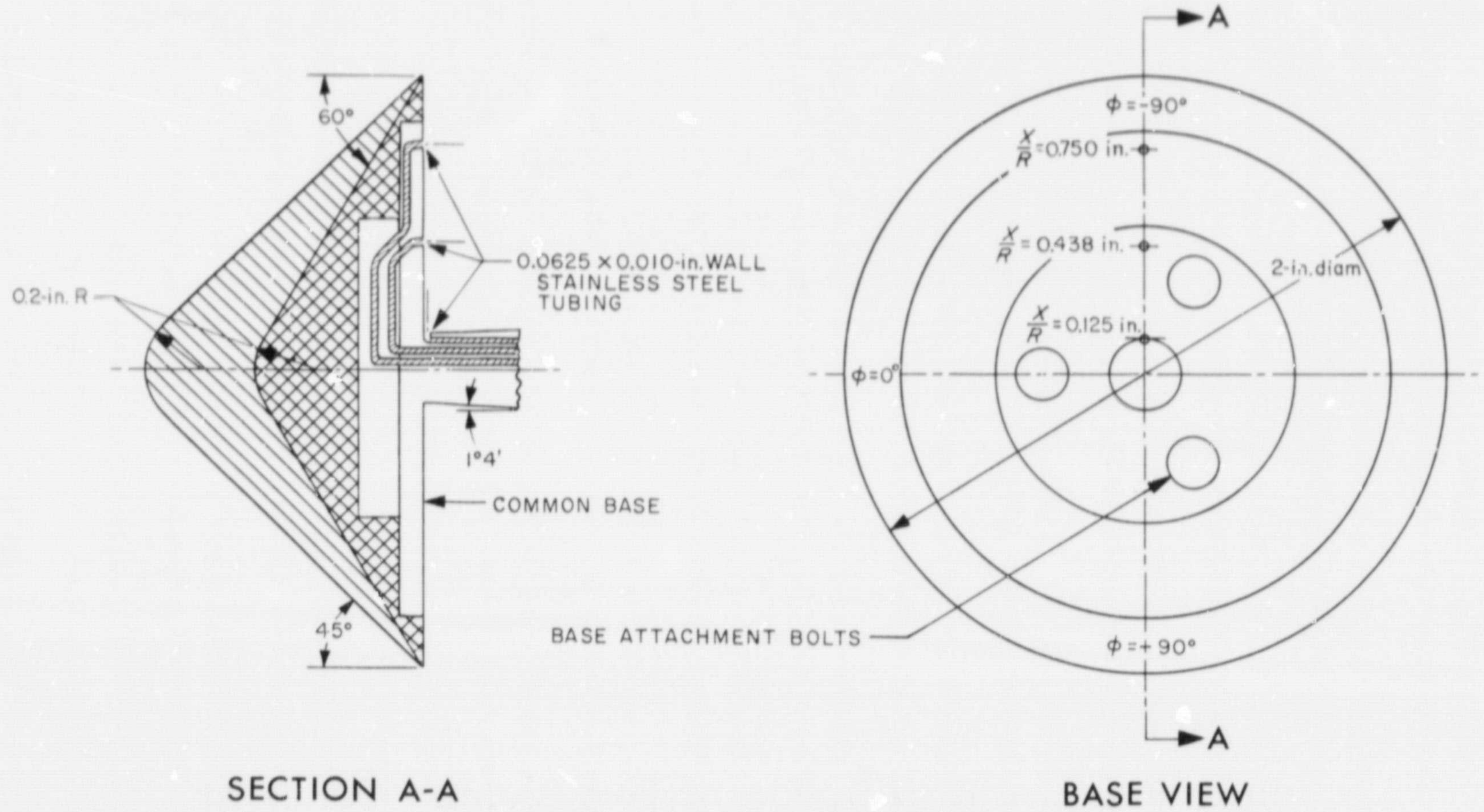


Fig. 1. Test models used in this investigation

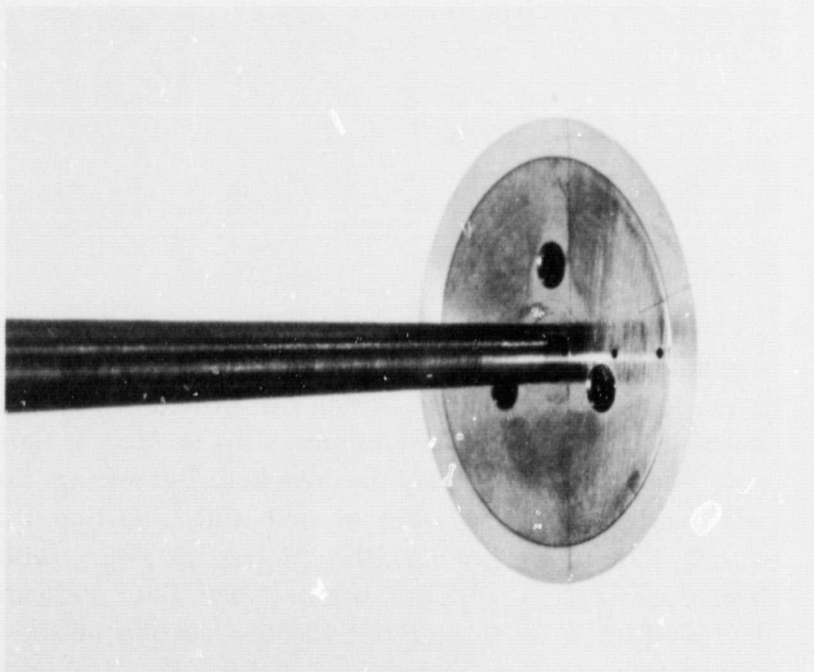


Fig. 2. Common base and sting mounting indicating geometry of base ports

tapered sting, which had a ¼-in. diameter at the model base. The sting was constructed in this manner to minimize the interference of the sting with the normal wake formation. The model-sting configuration thus represented the best arrangement practical for base pressure measurement on a blunt sting-mounted model in the 20-in. Supersonic Wind Tunnel. The 0.05-in. diameter pressure ports were aligned along a ray on the base-sting apparatus common to both models. The port nearest the sting was, in fact, on the interface of the sting and the base (Fig. 2). The tubes from these three ports were housed within the hollow sting in such a manner as to allow roll angles of ±90 deg without any interference or damage to them.

C. Test Procedure

The investigation was conducted at Mach numbers of 0.3, 0.5, 0.8, 1.81, 2.62, 3.49, and 3.51 with Reynolds numbers of 1.6×10^5, 2.7×10^5, 3.3×10^5, 3.3×10^5, 3.5×10^5, 0.4×10^5, and 3.4×10^5, respectively. The models were supported on a tapered sting with a sting end diameter to model base diameter ratio of 0.125 (Fig. 3). The hollow sting, which housed the three base pressure port tubes, was pitched to angles of attack of 0, 2, 4, 10, and 20 deg at each Mach number. To obtain a distribution over the base, the model was rolled through a total angle of 180 deg at 90-deg intervals at each angle of attack. With

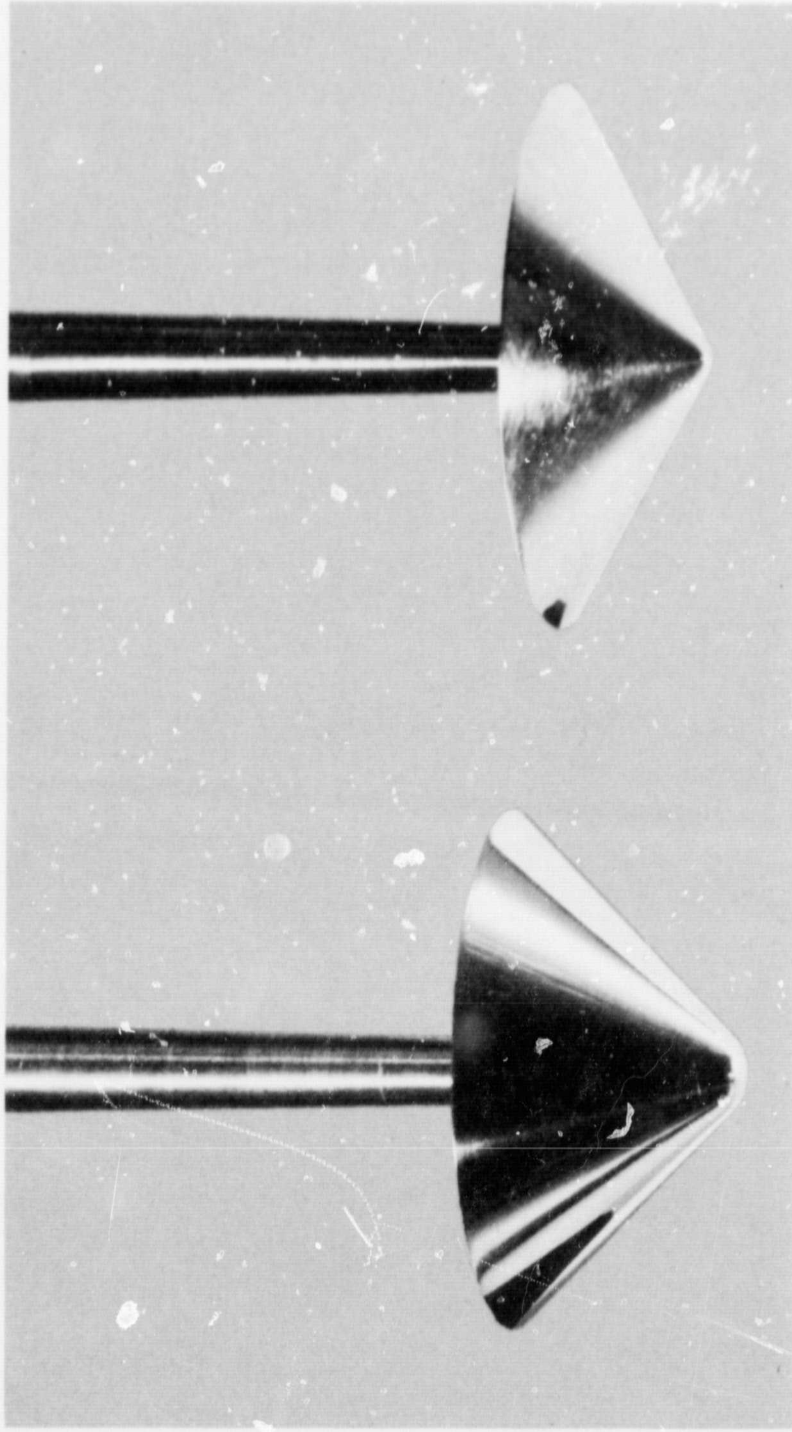


Fig. 3. The 60- and 45-deg cones mounted on tapered sting in JPL 20-in. Supersonic Wind Tunnel

the model at zero roll angle ($\phi = 0$), the base port ray was in a horizontal position; positive roll was then clockwise.

The JPL 100-port MPMS (multiple pressure measuring system), which is an updated version of the system described in Ref. 3, was employed to measure and record the base pressures. The system was advanced automatically after lag times had been established.

Several spark shadowgraphs were taken of both models at all Mach numbers in order to define and study the wake shapes and flows.

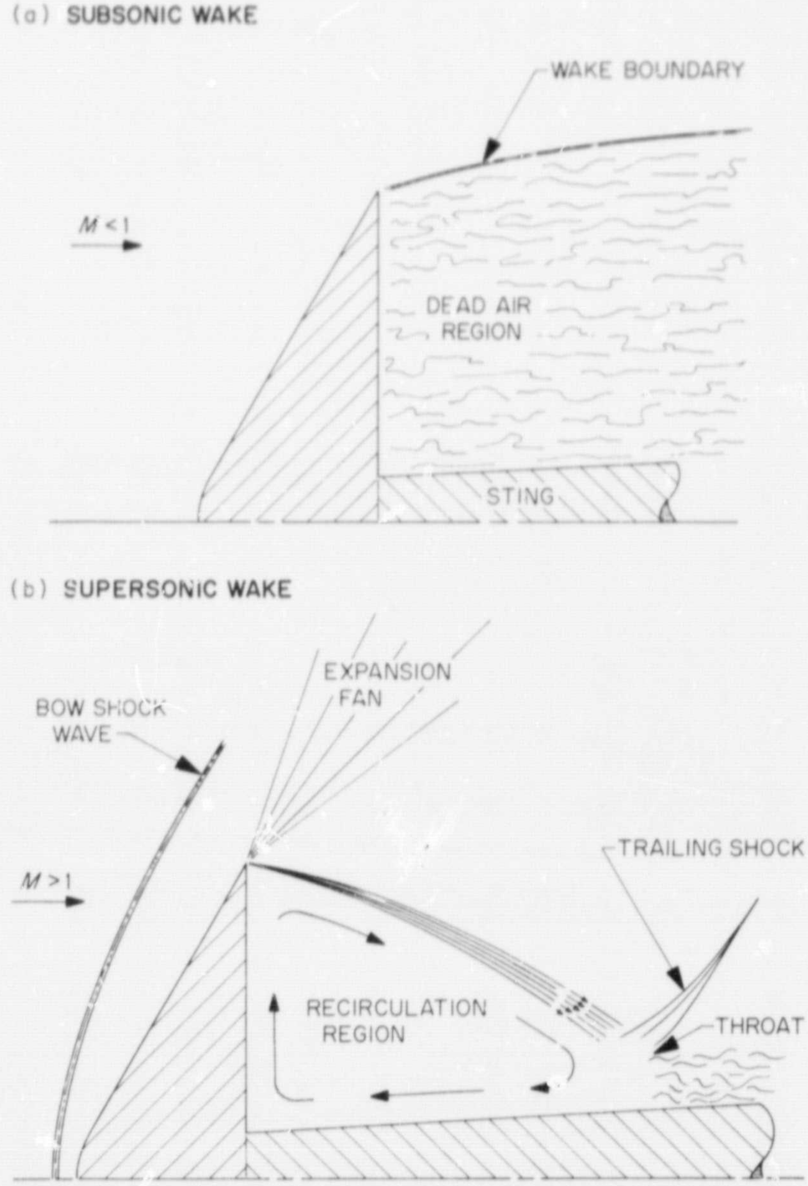


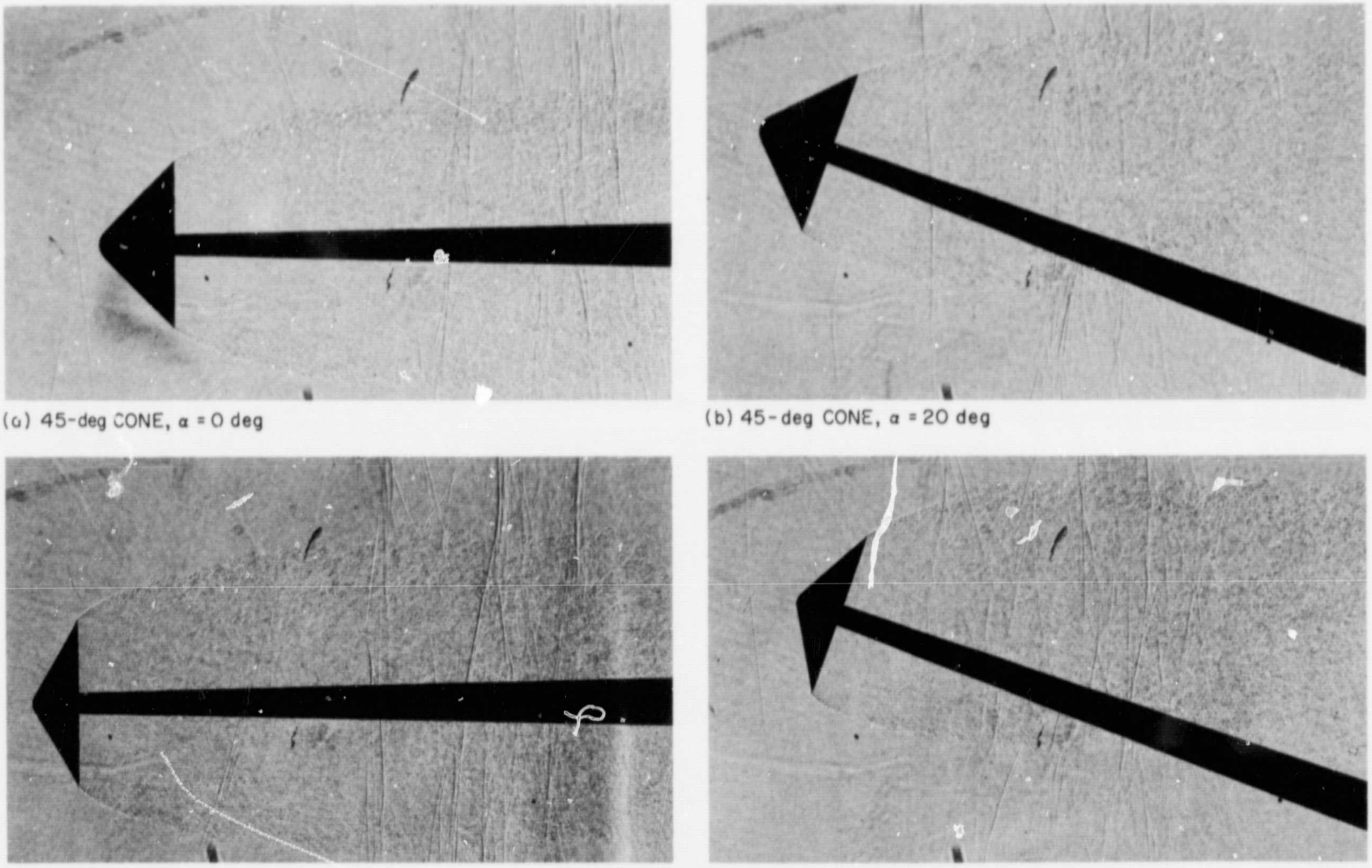
Fig. 4. Schematic of wake structure in subsonic flow and supersonic flow

III. Summary of Test Results

A. Wake Structure

The wake boundary behind a blunted cone at subsonic Mach numbers is very similar to that predicted by hydrodynamic free-streamline theory. That is, the flow sheds off the model edge and a wide eddying wake with no discernable neck or throat forms aft of the body (Fig. 4). Subsonically, the shape of this boundary is very insensitive to Mach number variation. A "dead air" region forms immediately behind the body in the near wake, and no reverse flow condition exists (Fig. 5).

The flow around the base and in the wake of a blunted cone at supersonic Mach numbers (Fig. 4b) is shown in the shadowgraphs (Figs. 6–8). An expansion fan



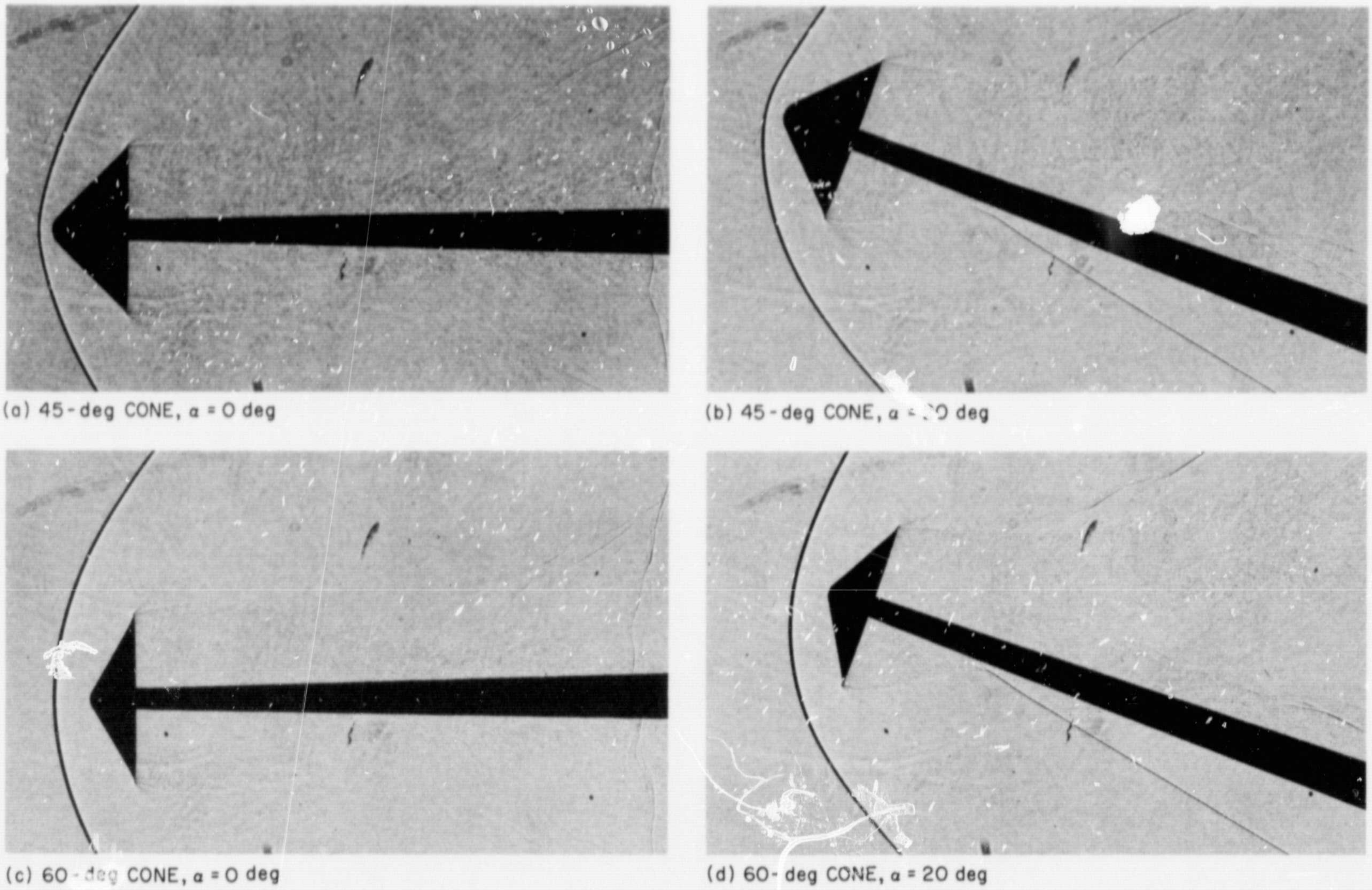
(a) 45-deg CONE, $\alpha = 0$ deg

(b) 45-deg CONE, $\alpha = 20$ deg

(c) 60-deg CONE, $\alpha = 0$ deg

(d) 60-deg CONE, $\alpha = 20$ deg

Fig. 5. Shadowgraphs indicating wake structure behind cones at $M = 0.8$ and $Re/in. = 0.34 \times 10^6$



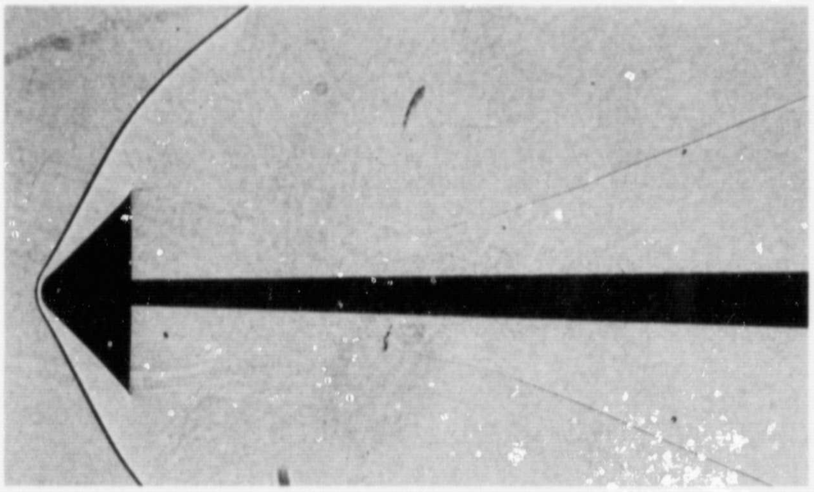
(a) 45-deg CONE, α = 0 deg

(b) 45-deg CONE, α = 20 deg

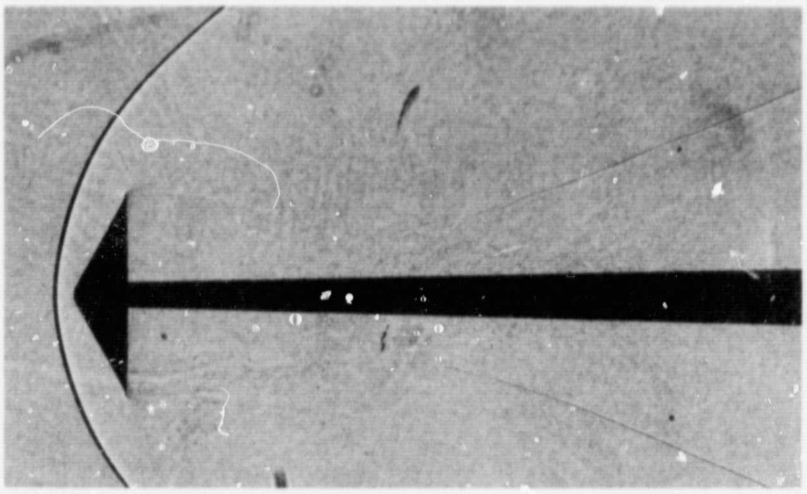
(c) 60-deg CONE, α = 0 deg

(d) 60-deg CONE, α = 20 deg

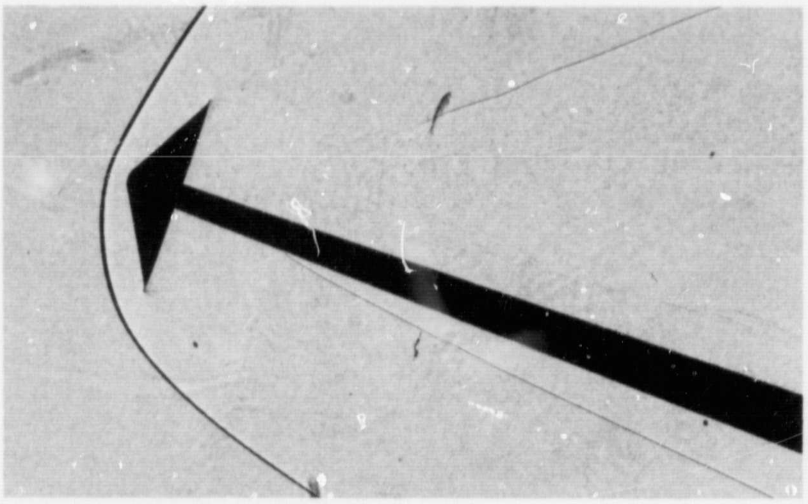
Fig. 6. Shadowgraphs indicating wake structure behind cones at $M = 1.81$ and $Re/\text{in.} = 0.34 \times 10^6$



(a) 45-deg CONE, α = 0 deg



(b) 60-deg CONE, α = 0 deg



(c) 60-deg CONE, α = 20 deg

Fig. 7. Shadowgraphs indicating wake structure behind cones at $M = 2.62$ and $Re/in. = 0.34 \times 10^6$

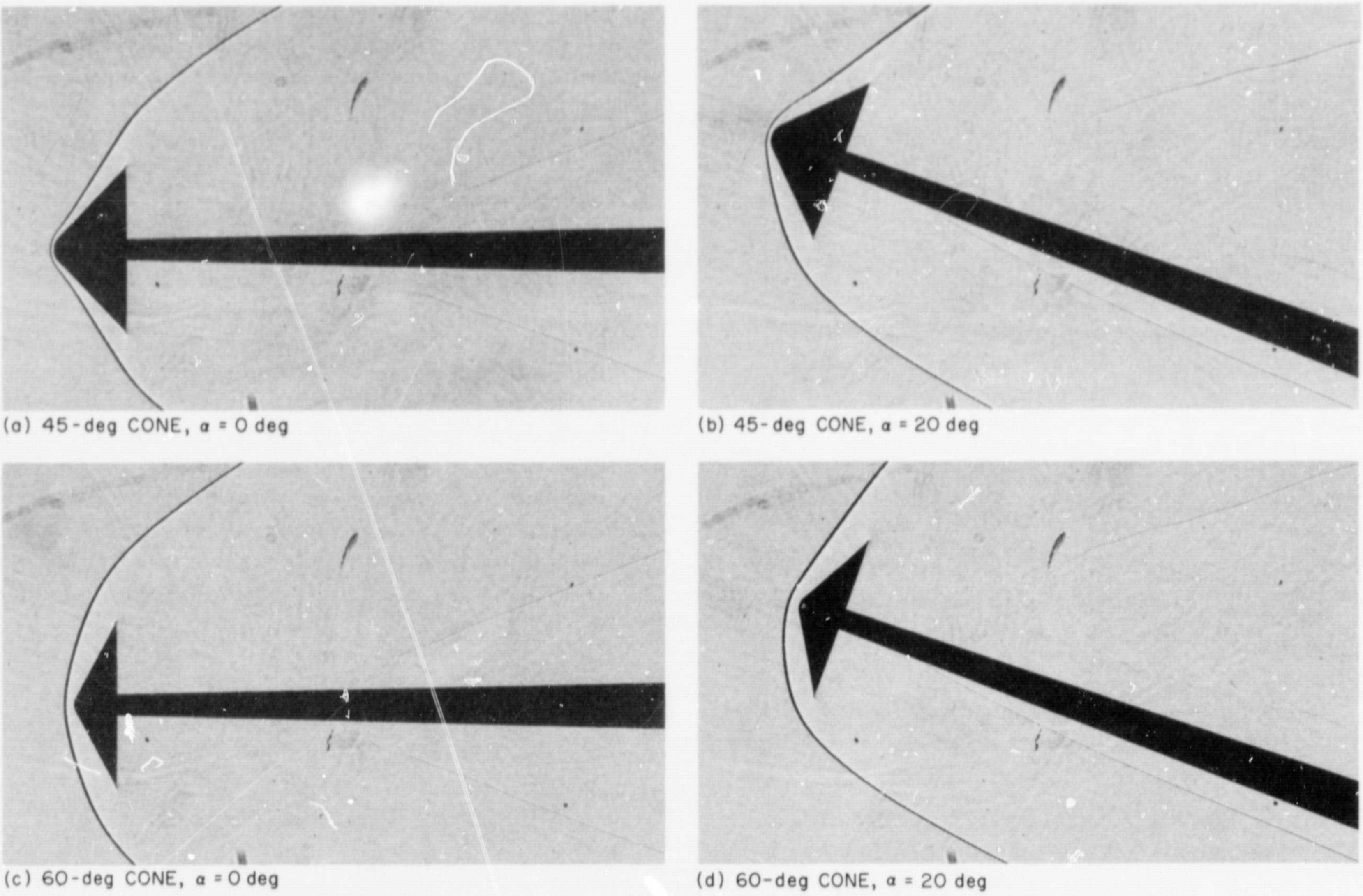


Fig. 8. Shadowgraphs indicating wake structure behind cones at $M = 3.51$ and $Re/in. = 0.34 \times 10^6$

results at the model edge as the flow is turned back towards the longitudinal body axis. At some distance aft of the model base, the wake necks down and a recompression shock is formed. The crosssectional area of this neck is a distinct function of Mach number in supersonic flows (Figs. 6–8). In general, it may be said that for supersonic flow the wake, and hence the base pressure, is determined by this critical region between the model base and the wake neck, where the streamlines turned through the edge expansion fan converge. The angle at which the streamlines converge is determined by a shock-wave boundary layer type of interaction at the neck. In this interaction, the streamlines assume the maximum expansion angle that the boundary layer energy can support as it negotiates the pressure rise through the recompression or trailing shock.

The base flow region is bounded by the body base and by the converging streamlines. Because of the viscosity of the fluid, the dead air is induced into a circulatory motion and a well-defined reverse-flow condition results. The viscous mixing causes the boundary layer to thicken as it approaches the wake throat. Downstream of the neck or throat, the wake core appears to maintain an essentially constant diameter except for occasional irregularities due to vortices, and is generally similar to a subsonic wake.

B. Mach Number Effect

Figure 9 presents the average base pressure ratio* as a function of Mach number for the two bodies at two angles of attack. Three phases are evident:

(1) A subsonic regime in which the ratio, though changing rapidly with Mach number, is quite insensitive to body shape and angle of attack in the ranges investigated.

*The average base pressure ratio seems to be a valid parameter as the complete data indicate very weak pressure dependence on port location in the area investigated.

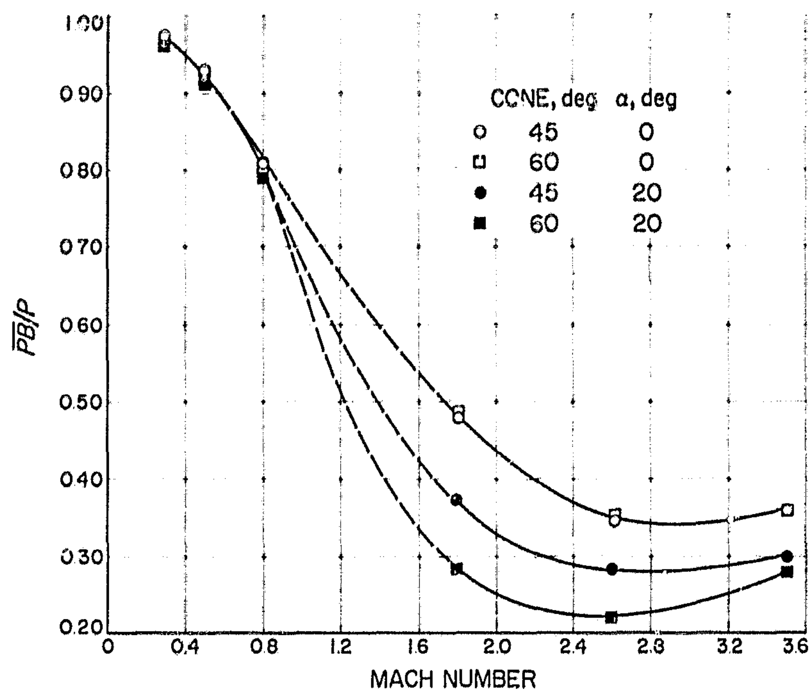


Fig. 9. Variation of average base pressure ratio with Mach number

(2) A transonic and low supersonic regime in which the effects of parameter variation become more distinct.

(3) As the Mach number is increased still further through 2.5, a minimum is reached and the gradient of the base pressure ratio reverses sign.

1. Subsonic regime. If one examines the region behind the base of a bluff body in subsonic flow, the pattern is found to be similar to that of a jet pump. The jet (formed by the outer flow), which is placed like a tube around the base region, mixes with the dead air and tries to "pump" it away. The dead air expands and the static pressure at the base of the body falls.

2. Transonic and low supersonic regime. Unlike the subsonic case, the shape of the wake boundary streamline in supersonic flow is a sensitive function of the Mach number. As the flow velocity is increased into the supersonic regime, the expansion fan at the model edge reduces the pressure. That is, the base pressure becomes a function of the wake boundary streamline turning angle. The body shape and angle of attack become important parameters.

3. Mach number greater than 2.5. It is interesting to note that the variation of the base pressure ratio as a function of Mach number becomes double valued at flow Mach numbers above 2.5. The value of the base pressure does, in fact, decrease monotonically with Mach number; however, the freestream static pressure with which it is ratioed decreases more rapidly. Hence, the gradient of the ratio changes sign and the function becomes double valued.

C. Reynolds Number Effect

Figure 10 indicates the effect of the Reynolds number on the base pressure ratio. Increasing the Reynolds number from 4×10^4 to 3.4×10^5 resulted in a 20% reduction of the ratio value at Mach 3.5. As the Reynolds number is increased from 10^5 to 10^6, a transition from a laminar to a turbulent type of mixing takes place along the wake for bodies with fineness ratio greater than 3 (Ref. 4). In the case of the bluff bodies investigated in this report, the transition occurs somewhat sooner. The near wake is then laminar at a Reynolds number of 4×10^4 and transitionally turbulent at a Reynolds number of 3.4×10^5. As

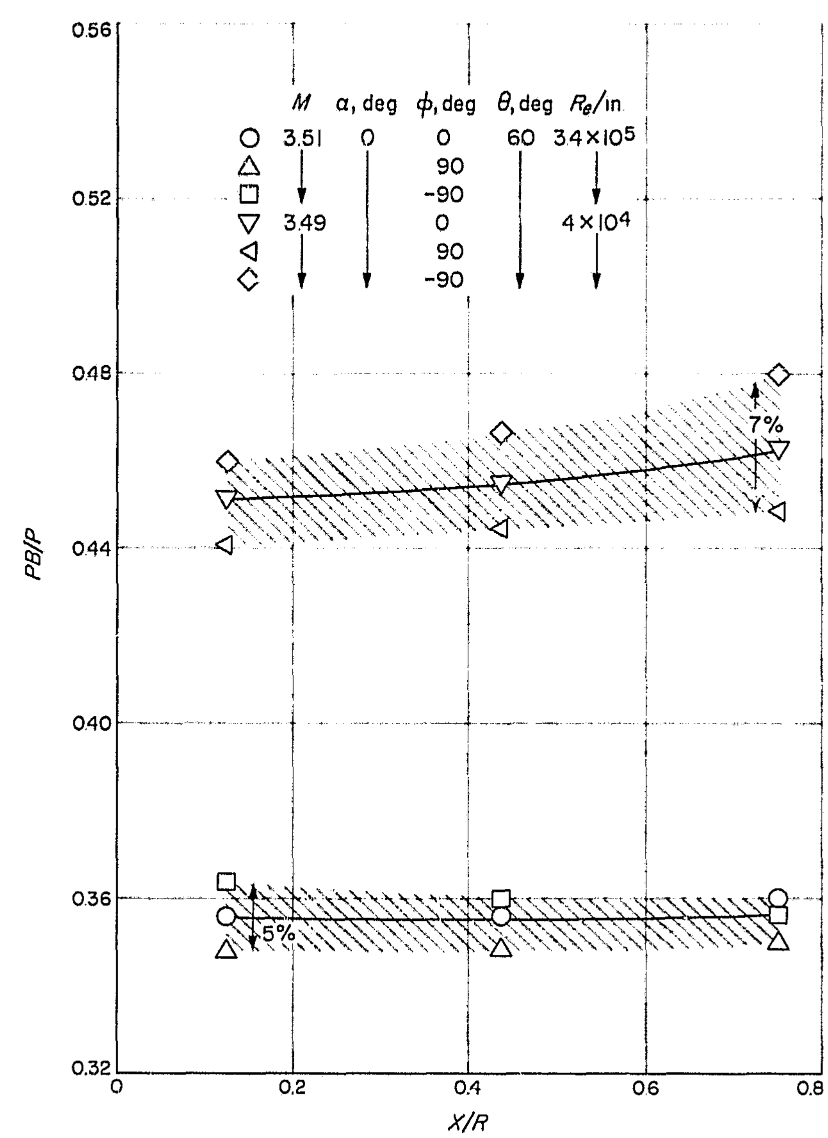


Fig. 10. Effect of Reynolds number on base pressure as a function of radial distance

this transition point moves toward the base and the intensity of the mixing increases, the base pressure falls and the ratio decreases accordingly.

Figure 10 also yields an indication of the data spread or repeatability. The base pressure ratio varied no more than 7 and 5% at the low and high Reynolds number conditions, respectively, over all nine port positions investigated.

D. Cone Angle Effect

A comparison of the base pressure data for the two bodies as a function of angle of attack at two Mach numbers is presented in Fig. 11. It is clear that in the subsonic case ($M = 0.5$) the base pressure ratio is extremely insensitive to cone angle in the area investigated. Also, cone angle has no significant effect in the typical supersonic case ($M = 1.81$) for angles of attack ≤ 4 deg. Beyond 4 deg, the curves diverge and the 60-deg cone experiences a lower base pressure. This effect is consistent with the hypothesis that the base pressure is a function of the expansion angle necessary to turn the flow back along the wake boundary.

E. Angle of Attack Effect

Considering again Fig. 11, it is apparent that, through the range investigated, the angle of attack is not a significant parameter in the determination of base pressure on the two bodies tested at subsonic Mach numbers. The example shown at $M = 0.8$ is typical. In the supersonic

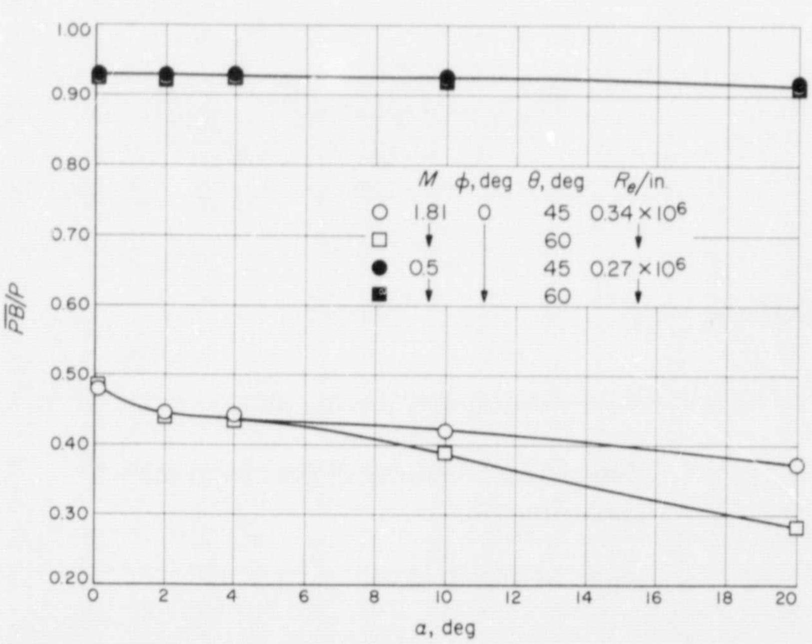


Fig. 11. Variation of average base pressure ratio with angle of attack at two Mach numbers

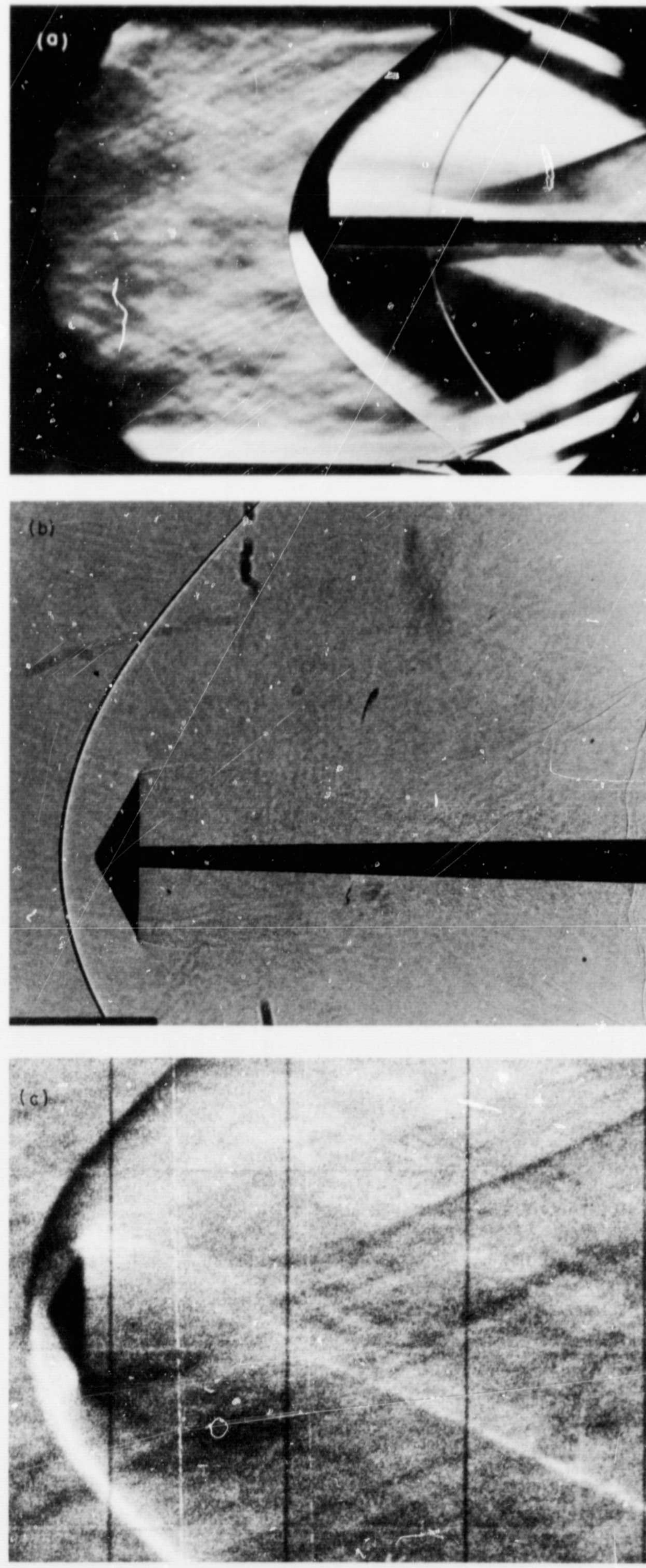


Fig. 12. Wake structure comparison for two sting and one free-flight configurations at $M = 2.0$

regime, however, the ratio varied as much as 40% over the range investigated. Both bodies displayed the base pressure ratio as similar, monotonically decreasing functions of the angle of attack.

F. Sting Effect

A knowledge of the possible support interference effects is necessary for a satisfactory interpretation of the wind tunnel measurements. The effect on base pressure is a complicated function of the ratio of the diameter of the support rod to the base diameter, the Mach number, and the Reynolds number. The sting diameter is of major importance as it affects the formation of the wake neck. At transonic and low supersonic Mach numbers, a large diameter support tends to fill and "close" the neck, thereby, decreasing the base pressure. This trend tends to reverse itself as hypersonic Mach numbers are approached and the boundary layer along the sting and wake boundary thicken.

Figures 12a and 12b indicate the influence of sting diameter on wake formation in low supersonic flow. In a noninterference condition, the wake neck diameter is inversely proportional to the Mach number in this range. Here, however, the larger sting ($d_{st}/D = 0.3$) at $M = 2.2$ prevents the wake from closing as much as the smaller sting ($d_{st}/D = 0.2$) at $M = 1.8$. Figure 12c indicates the wake shape for a similar configuration in free flight at $M = 2.0$.

The wake neck diameter resulting from this interference-free test method appears to be very similar to that resulting from the type of support employed in this investigation in this Mach numbers region. The tapered sting configuration resulted in the best arrangement possible for base pressure measurements on sting-mounted blunt models in the 20-in. Supersonic Wind Tunnel. At higher Mach numbers, as the wake neck diameter approaches the sting diameter, even very slender support rods will have a more significant effect on the wake formation. At subsonic Mach numbers, a normal sting support (sting diameter less than one-half the body base diameter) exhibits little or no wake interference in the base region.

IV. Conclusions

The following conclusions are presented for this study:

(1) The shape of the subsonic wake boundary is quite insensitive to Mach number variation in the range investigated.

(2) Although the subsonic base pressure ratio decreases rapidly with Mach number, it is highly insensitive to small variations in body shape and angle of attack.

(3) The shape of the supersonic wake boundary is a function of the Mach number, and the diameter of the wake throat varies inversely as the Mach number.

(4) Body shape and angle of attack can become significant parameters in the supersonic regime.

(5) In the transitional Reynolds number regime (approximately $Re = 10^5$ to 10^6), the base pressure ratio decreases with increasing Reynolds number.

(6) The tapered sting configuration resulted in the best arrangement possible for base pressure measurements on sting mounted blunt models in the 20-in. Supersonic Wind Tunnel. Until the actual base pressure is measured on "unsupported" models (such as that telemetered from free-flight models or from models supported by a magnetic field), it is not possible to quantitatively assess the validity of data obtained with this optimum sting geometry.

Nomenclature

D	model base diameter, in.
d_{st}	sting diameter, in.
M	Mach number
P	freestream static pressure, psi
PB	base pressure ($\overline{PB}$ = average of three base ports), psi
R	model base radius, in.
Re/in.	Reynolds number per in., $\rho V/\mu$
X	dimensional distance of port from model centerline, in.
α	angle of attack, deg
θ	cone half-angle, deg
ϕ	angle of roll, deg

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